

# Laboratory Studies of Angular Momentum Transport in Astrophysical Accretion Disks

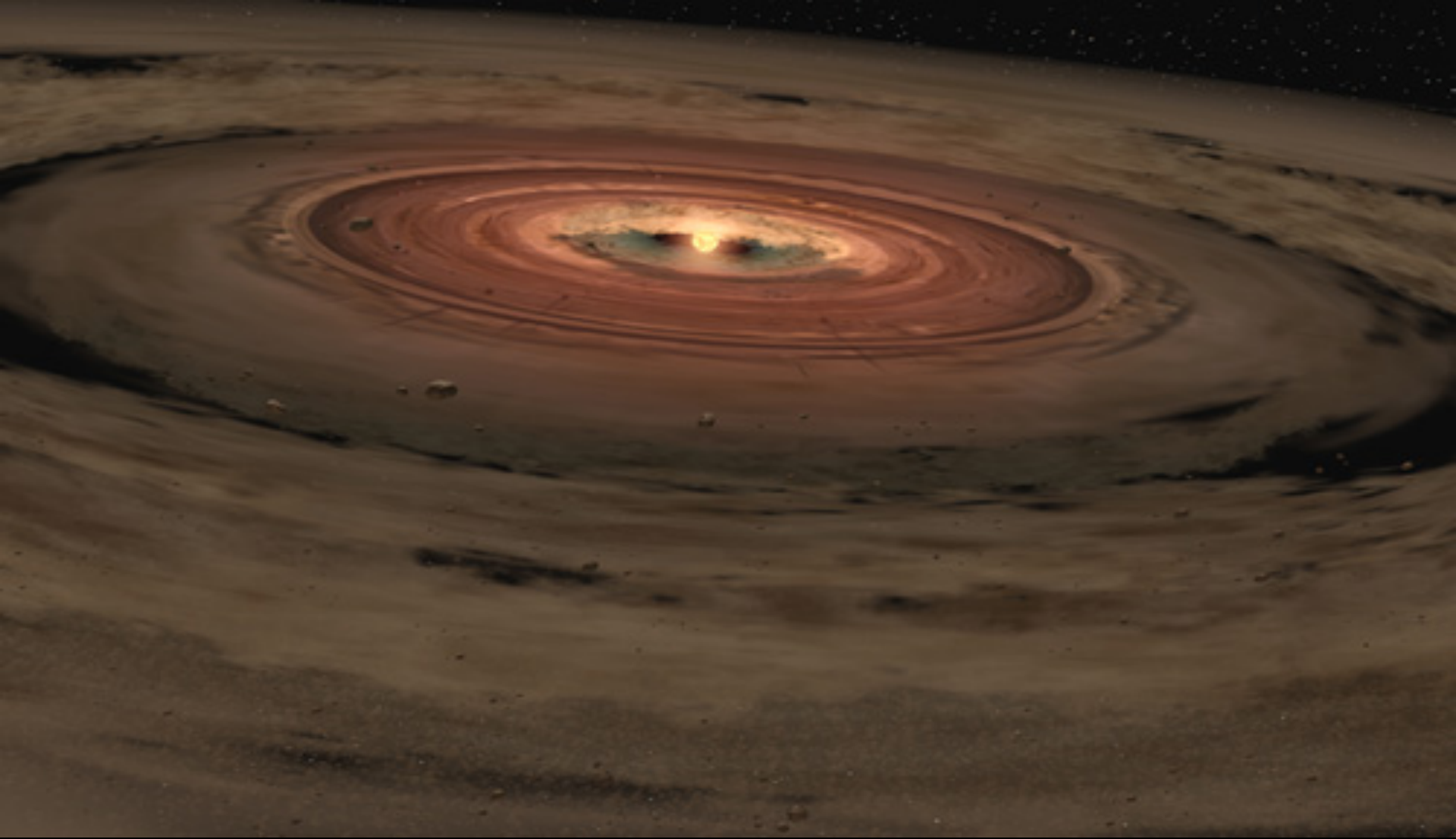
**Hantao Ji**

*Princeton University*



Fermilab Colloquium  
September 17, 2014





*Biology and astronomy are retirement of physicists.*

— *Steven Chu (2004)*  
*(1997 physics Nobel laureate)*

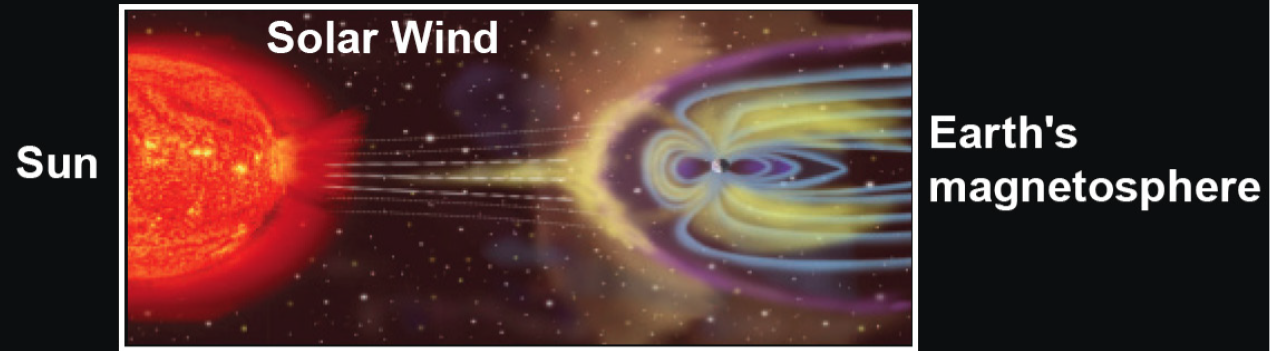
# Angular momentum transport in astrophysics and in the lab

Hantao Ji and Steven Balbus

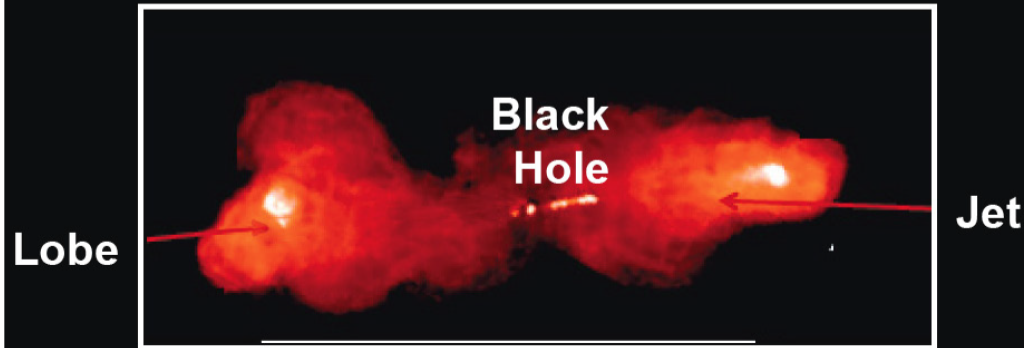
For evolving astrophysical accretion disks to concentrate their mass and still conserve angular momentum, turbulent flows are crucial. Those flows cannot be directly observed, so to understand them better physicists are creating them in modest-sized laboratory experiments.

# Plasma pervades the universe at all scales

Heliophysics  
( $<10^{-4}$  light year)



Astrophysics  
( $>10^6$  light year)



**Plasma astrophysics:** understanding our visible universe via plasma physics  
It addresses the third important question in the universe:

Dark energy drives expansion of the universe

Dark matter controls largest structures of the universe

**Plasma processes are key in deciding much of the rest**



# 10 Major Plasma Astrophysics Questions

<http://www.pppl.gov/conferences/2010/WOPA>

1. How do magnetic explosions work?
2. How are cosmic rays accelerated to ultrahigh energies?
3. What is the origin of coronae and winds in virtually all stars, including Sun?
4. How are magnetic fields generated in stars, galaxies, and clusters?
5. What powers the most luminous sources in the universe?
6. How is star and planet formation impacted by plasma dynamics?
7. How do magnetic field, radiation and turbulence impact supernova explosions?
8. How are jets launched and collimated?
9. How is the plasma state altered by ultra-strong magnetic field?
10. Can magnetic fields affect cosmological structure formation?

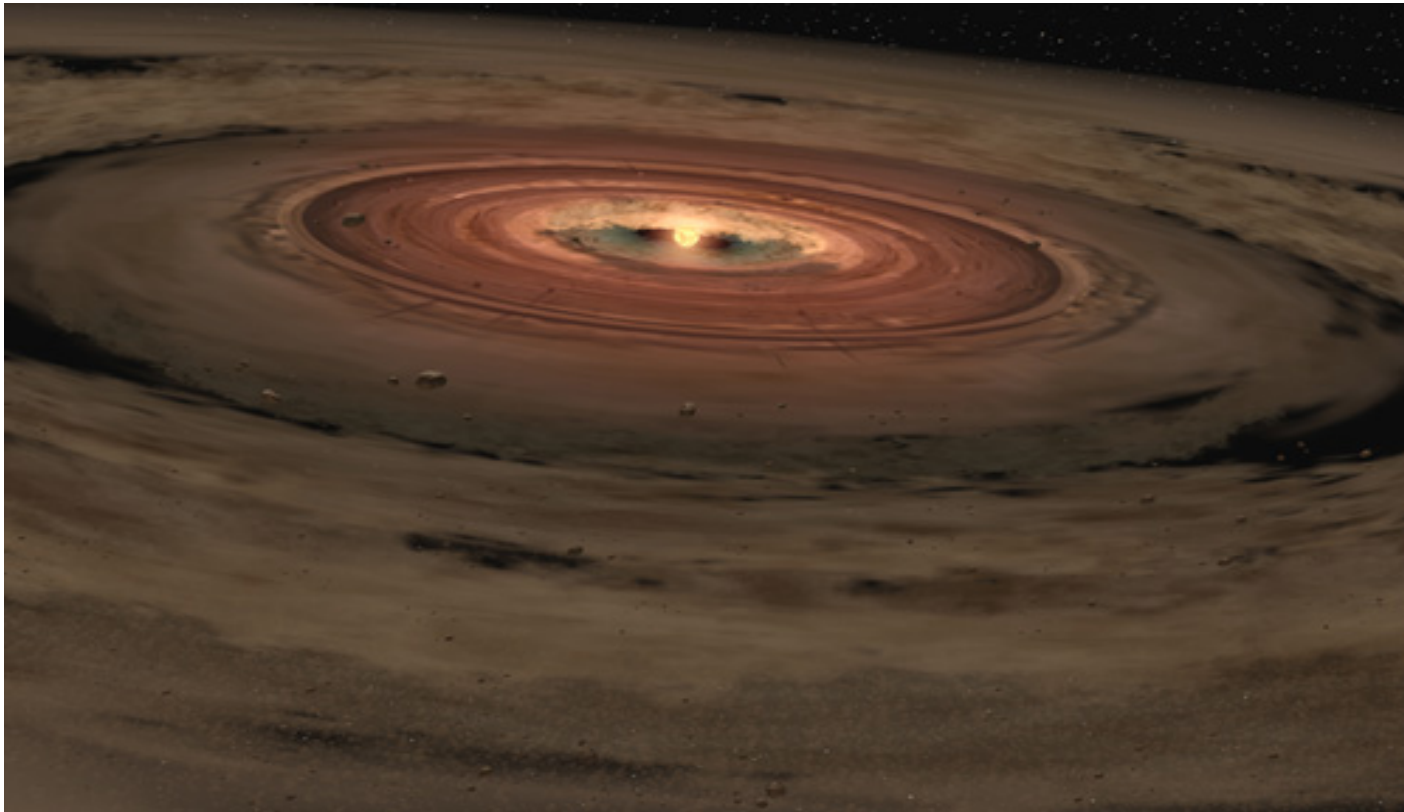
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# Outline

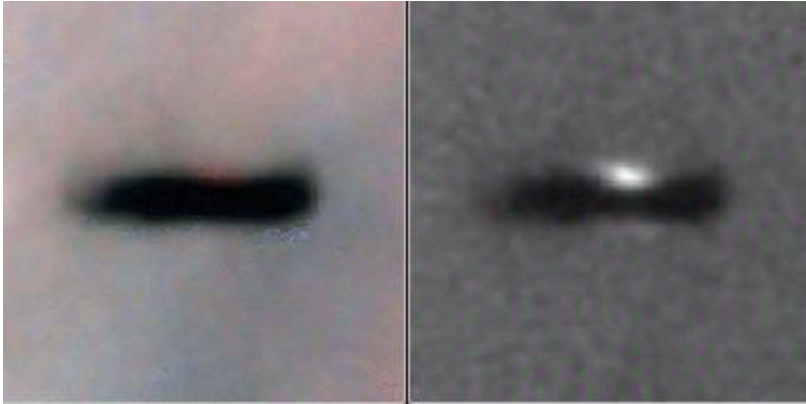
- **Angular momentum transport in accretion disks and why laboratory flows can be relevant**
- **Hydrodynamic experiments**
  - Long history, but relevant results emerged only recently
- **Magnetohydrodynamic (MHD) experiments**
  - Started recently, beginning to generate interesting results
- **Gas and plasma experiments**
  - Explorations just began
- **Summary and future**

**An accretion disk** is a disk structure made of gas, dust and plasma rotating around and gradually falling (accreting) onto a central object.





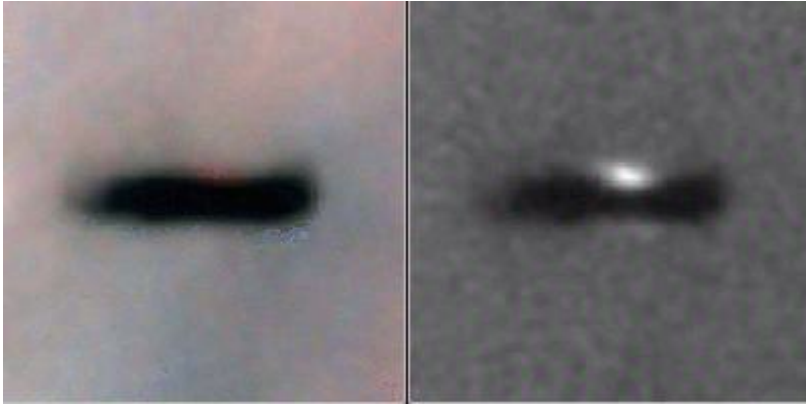
# Important Astrophysical Processes Happen in Accretion Disks



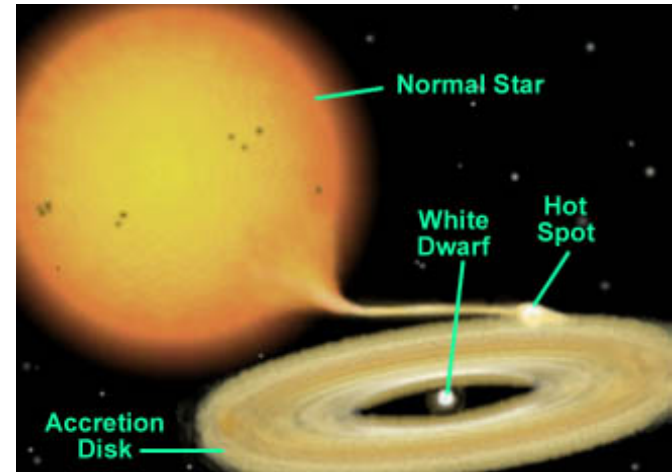
**Formation of stars and  
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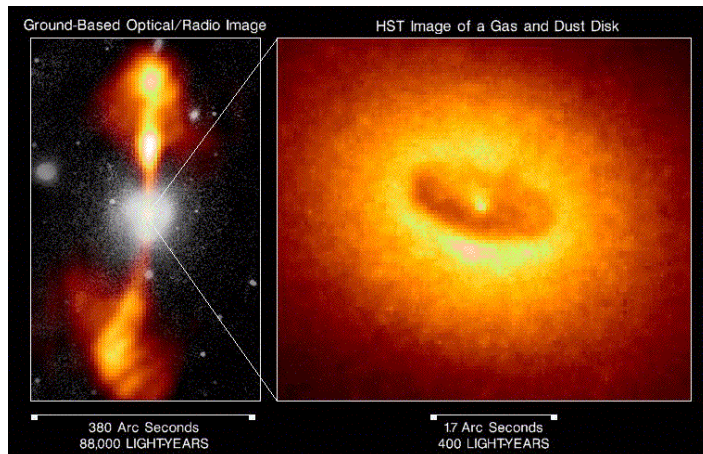
# Important Astrophysical Processes Happen in Accretion Disks



**Formation of stars and planets in proto-star systems**



**Mass transfer and energetic activity in binary stars**



**Release of energy in active galactic centers around a supermassive black hole (*as luminous as  $10^{15}$  of Sun, brightest steady source in the Universe*)**

# Accretion Disks Power Most Luminous Sources in the Universe

Efficiency in the unit of  $mc^2$ :

- Chemical reaction:  $\sim 10^{-10}$
- Accretion to solar-type stars:  $\sim 10^{-6}$
- Nuclear fission:  $\sim 0.08\%$
- Nuclear fusion:  $\sim 0.4\%$ (DT),  $0.7\%$ (H)
- Accretion to neutron stars & black holes: 5–40%
- Matter anti-matter annihilation: 100%



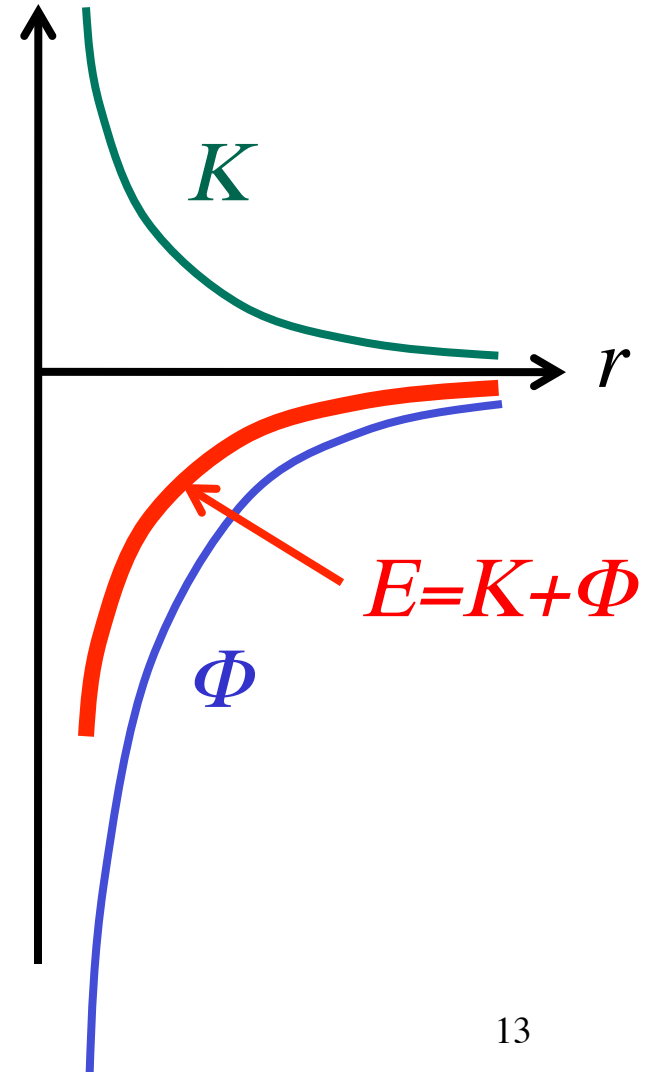
# Why Accretion Can Release Energy?

- Kepler's Third Law: "The square of the orbital period of a planet is directly proportional to the cube of the semi-major axis of its orbit"

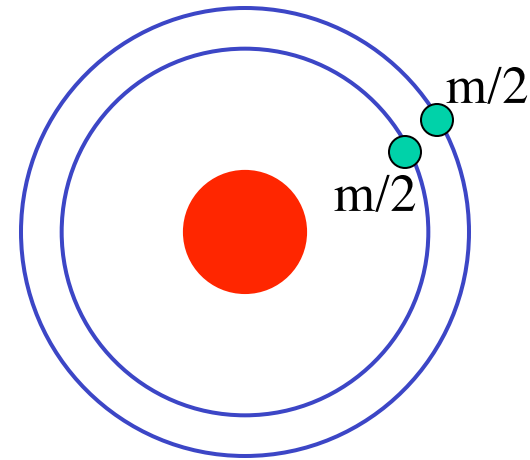
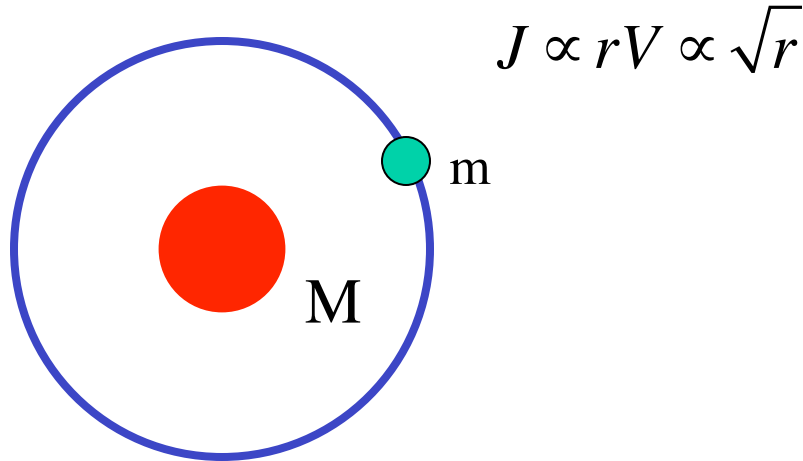
$$\frac{1}{\Omega^2} \propto r^3 \quad \text{or} \quad \Omega = \sqrt{\frac{GM}{r^3}}$$

- Energy can be released by falling closer to the center

$$\begin{aligned} E = K + \Phi &= \frac{1}{2} m (\Omega r)^2 - \frac{GMm}{r} \\ &= \frac{GMm}{2r} - \frac{GMm}{r} = -\frac{GMm}{2r} < 0 \end{aligned}$$



# But how about angular momentum conservation?



$$\frac{J_0}{\sqrt{GM}} = m\sqrt{r}$$

$$\frac{J_0/2}{\sqrt{GM}} = \frac{m}{2}\sqrt{r}$$

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$$J_0/2 + J_0/2 = J_0$$

$$\frac{J_0/2 + \delta J}{\sqrt{GM}} = \frac{m}{2}\sqrt{r + \delta r_1}$$

$$\frac{J_0/2 - \delta J}{\sqrt{GM}} = \frac{m}{2}\sqrt{r - \delta r_2}$$

$$(J_0/2 + \delta J) + (J_0/2 - \delta J) = J_0$$

$$\frac{E_0}{GM} = -\frac{m}{2r}$$

$$\frac{E_0/2}{GM} = -\frac{m}{4r}$$

$$\frac{E_0/2}{GM} = -\frac{m}{4r}$$

$$E_0/2 + E_0/2 = E_0$$

$$-\frac{m}{4(r + \delta r_1)} - \frac{m}{4(r - \delta r_2)} = -\frac{m}{4r} \left( \frac{r}{r + \delta r_1} + \frac{r}{r - \delta r_2} \right)$$

$$= -\frac{m}{4r} \left[ \left( 1 + \frac{2\delta J}{J_0} \right)^{-2} + \left( 1 - \frac{2\delta J}{J_0} \right)^{-2} \right] \approx -\frac{m}{2r} \left[ 1 + 12 \left( \frac{2\delta J}{J_0} \right)^2 \right] < \frac{E_0}{GM}$$

**It can be redistributed or transported!**

# The Common Puzzle: Why accretion is **fast**?

- Equivalent to the question why the **angular momentum** outward transport is fast

*compared to:*

- The transport which can be supported by molecular (classical) viscosity

*therefore:*

- **Turbulence** is required to generate enhanced “viscosity”

*however:*  $(J \propto r^2 \Omega \propto r^{1/2})$

- The Keplerian disks are **linearly stable** hydrodynamically at any  $Re\#$ 's, satisfying Rayleigh's stability criterion of  $dJ/dr > 0$

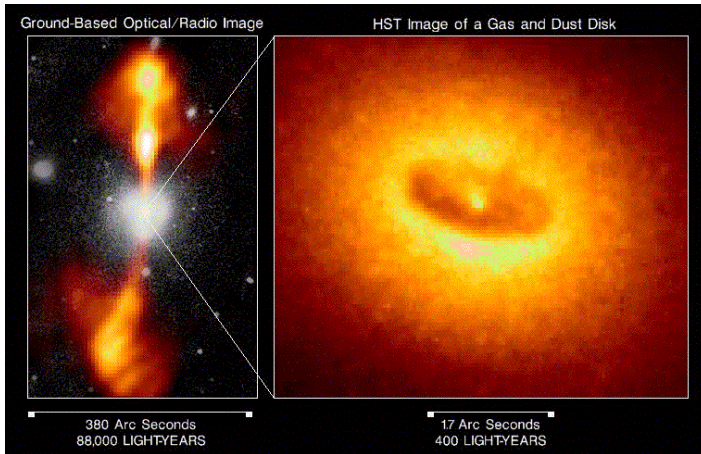
*The Key Question:*

**How to generate turbulence to  
transport angular momentum in  
Keplerian disks?**



# Two Main Candidate Mechanisms to Generate Turbulence in Accretion Disks

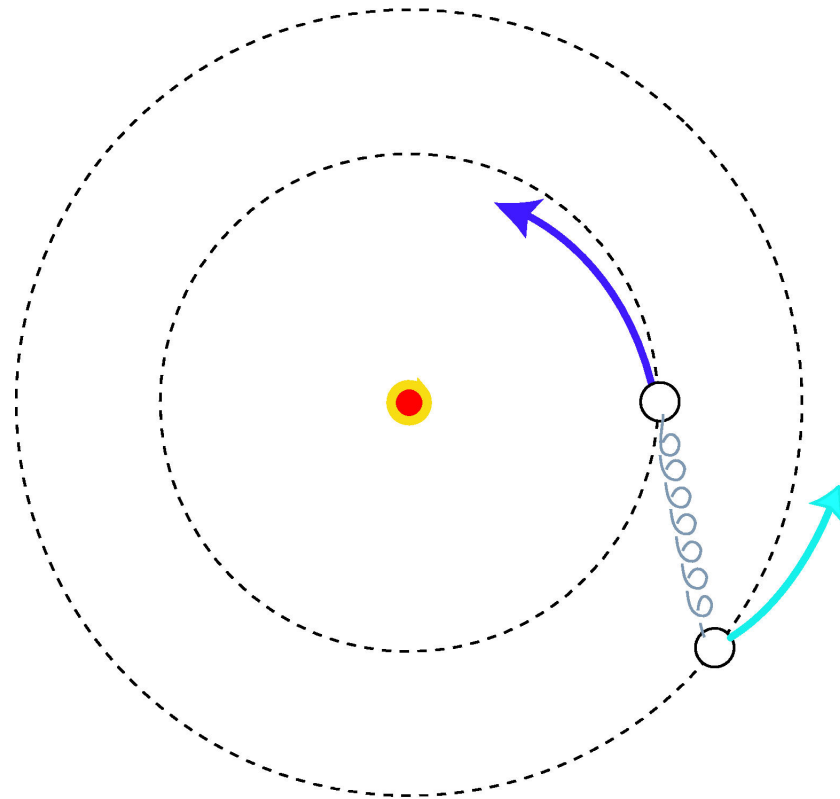
Hot disks such as quasar or Active Galactic Nuclei disks



**Magnetorotational Instability (MRI)**

# An Intuitive Picture of MRI

- **Radially and azimuthally displaced fluid elements are linked by a spring (magnetic field)**
- **Fast element is slowed and slow element is fastened, transferring angular momentum**
- **Initial displacements are amplified  $\rightarrow$  instability!**
- **Stable if the spring is too strong**



# A Toy Model of MRI

Based on Balbus (2009), Scholarpedia, 4(7):2409

- Displacements  $x$  and  $y$  ( $\ll R$ ) in radial and azimuthal directions, respectively.
- With spring constant per mass  $K$ , equations of motion take the form:

$$\ddot{x} - 2\Omega\dot{y} = -xr \frac{d\Omega^2}{dr} - Kx$$

$$\ddot{y} + 2\Omega\dot{x} = -Ky$$

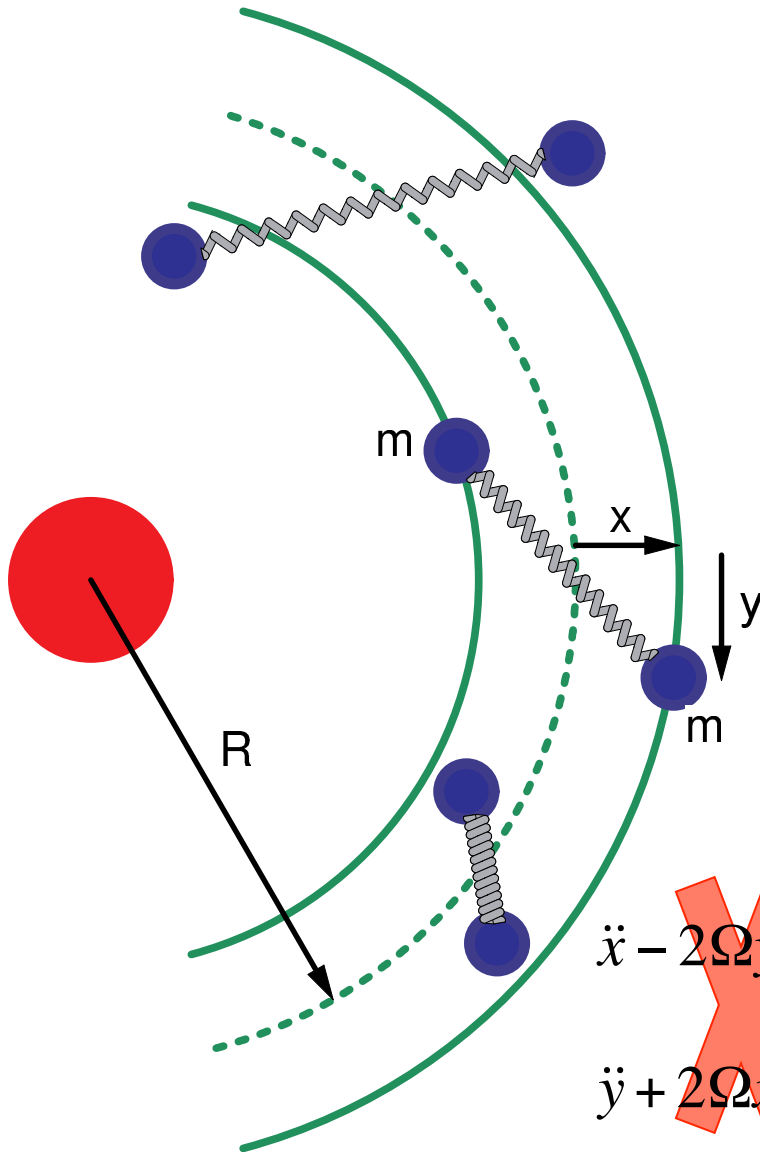
$$\begin{aligned} \ddot{x} - 2\Omega\dot{y} &= 0 \\ \ddot{y} + 2\Omega\dot{x} &= 0 \end{aligned} \quad \text{Gyration with a frequency of } 2\Omega; \text{ “epicyclic motion”}$$

$$\ddot{x} - 2\Omega\dot{y} = -\left(K + r \frac{d\Omega^2}{dr}\right)x$$

Ignoring or “averaging over” gyration, unstable if

$$\ddot{y} + 2\Omega\dot{x} = -Ky$$

$$K + r \frac{d\Omega^2}{dr} < 0 \Rightarrow r \frac{d\Omega^2}{dr} < -K \rightarrow 0$$



# MRI Dispersion Relation

From the toy model at frequency  $\omega$ :

$$\omega^4 - (2K + \kappa^2)\omega^2 + K\left(K + r\frac{d\Omega^2}{dr}\right) = 0$$

Related to the 1996 NASA tethered satellite accident?

From ideal magneto-hydrodynamics (MHD):

$$\omega^4 - (2k^2V_A^2 + \kappa^2)\omega^2 + k^2V_A^2\left(k^2V_A^2 + r\frac{d\Omega^2}{dr}\right) = 0$$

Balbus & Hawley (1991)

...with finite viscosity and resistivity:

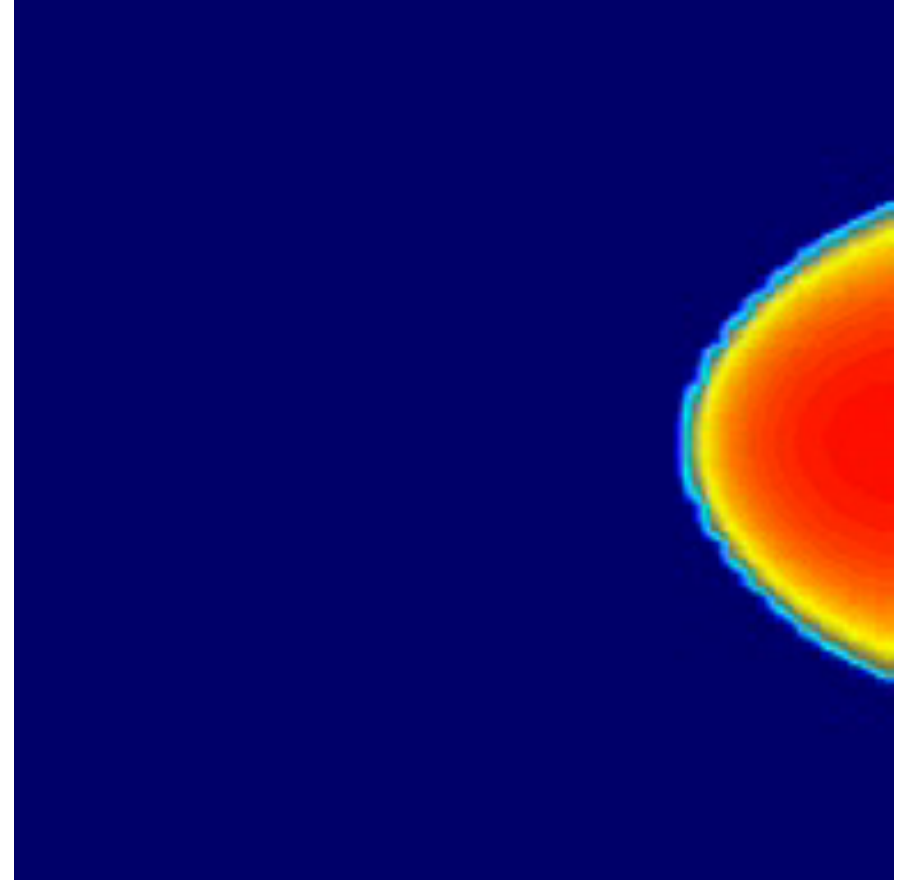
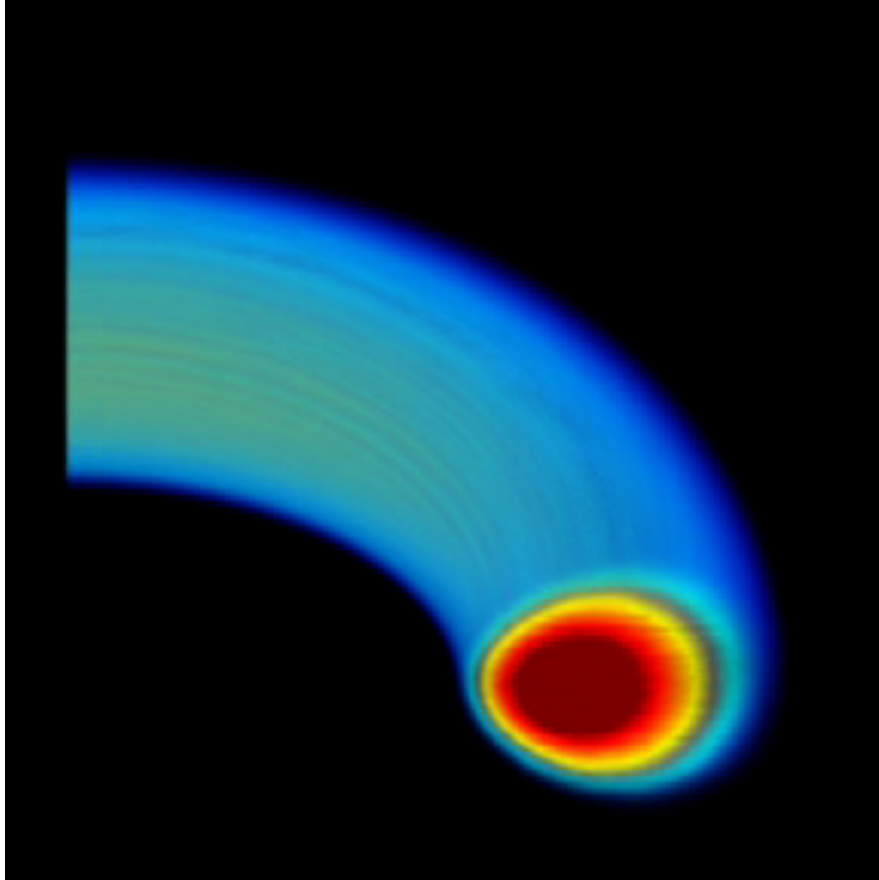
$$\left[(\gamma + \nu k^2)(\gamma + \eta k^2) + k^2V_A^2\right]^2 + \kappa^2(\gamma + \eta k^2)^2 + r\frac{d\Omega^2}{dr}k^2V_A^2 = 0$$

Ji, Goodman, & Kageyama (2001)



# MRI Demonstrated in Numerical Simulations

*3D MHD simulations by John Hawley*

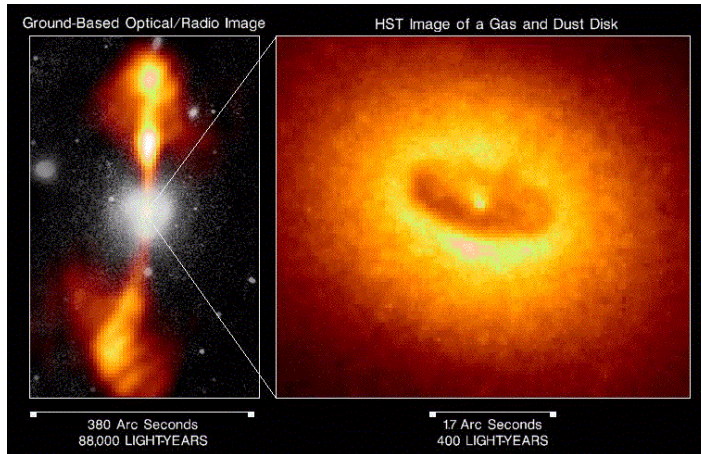


2013 Shaw Prize for Astronomy: S. Balbus & J. Hawley

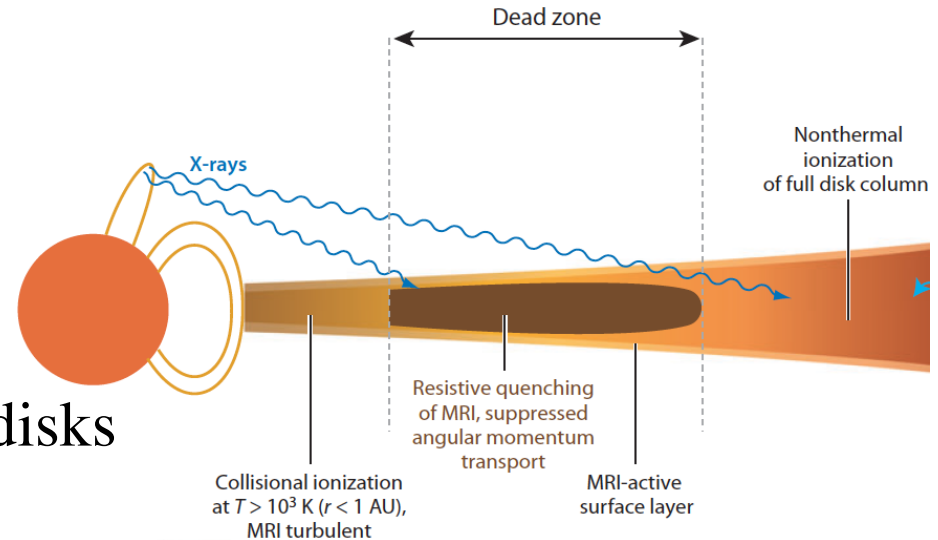
“for their discovery and study of the magnetorotational instability, and for demonstrating that this instability leads to turbulence and is a viable mechanism for angular momentum transport in astrophysical accretion disks”

# Two Main Candidate Mechanisms to Generate Turbulence in Accretion Disks

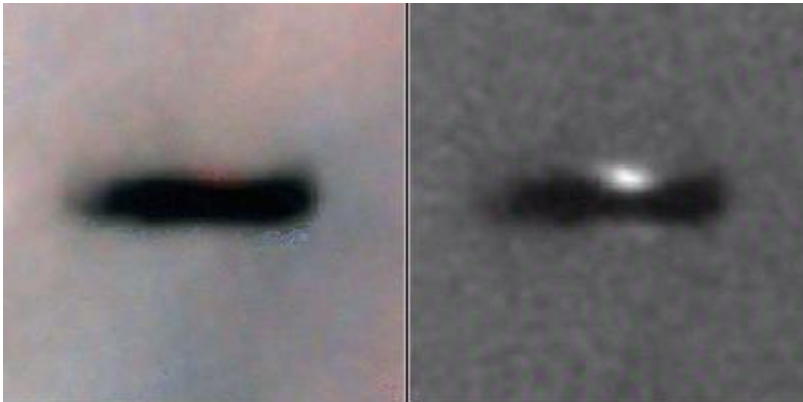
Hot disks such as quasar or Active Galactic Nuclei disks



## Magnetorotational Instability (MRI)



Cold disks such as protoplanetary disks

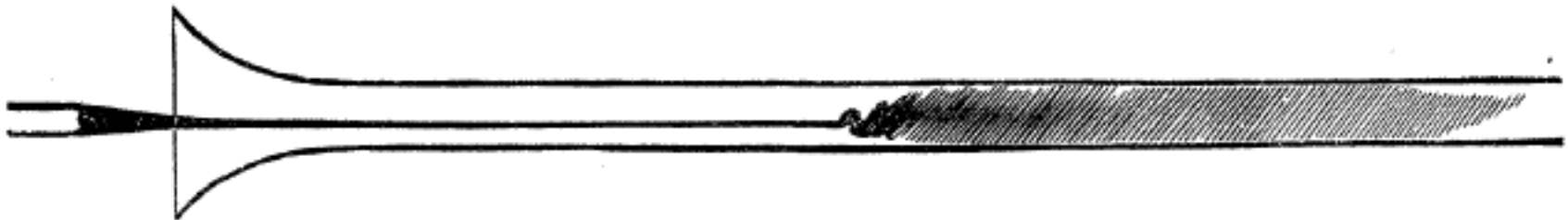
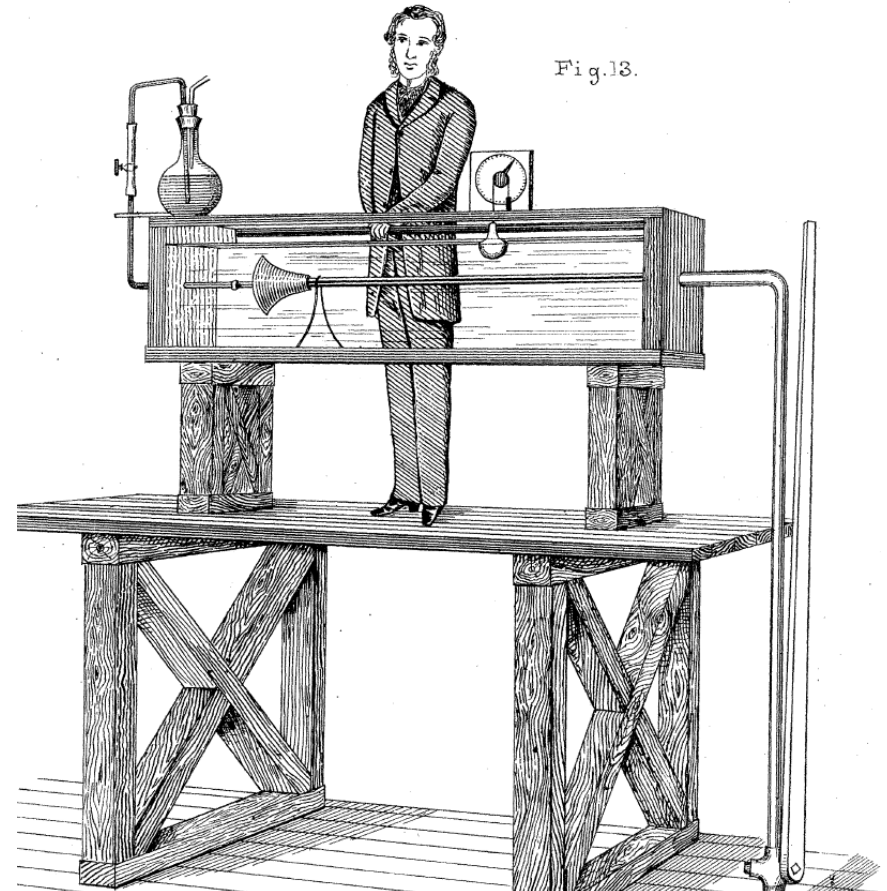


## Nonlinear hydrodynamic instabilities

- Terrestrial flows (e.g. pipe flows) are often nonlinearly unstable if  $Re > 10^2$ - $10^4$  despite linear stability<sub>22</sub>

# Turbulence in Pipe Flows

- First detailed experiments by Reynolds (1883)
- Turbulence sets in when  $Re > \sim 2000$ .
- But they are linearly stable at arbitrarily large  $Re$ !
- Identified as nonlinear or subcritical transitions to turbulence.



Direct astronomical observations or  
direct numerical simulation of MRI or  
Nonlinear Hydro Instabilities in disks are  
still not yet possible

Can they be tested and studied  
in the lab?

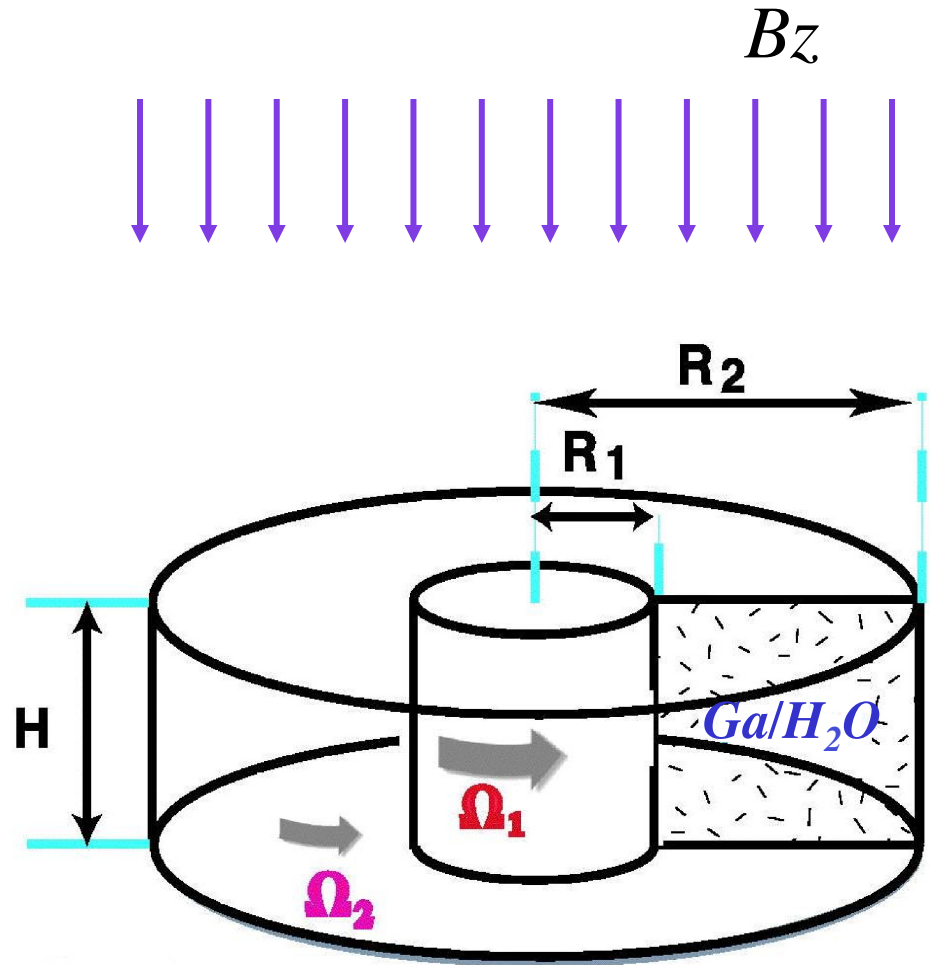
# The Basic Experimental Idea

- Create (quasi-)Keplerian flows in a cylindrical geometry (i.e. Taylor-Couette):

$$\Omega_1 > \Omega_2$$

$$R_1^2 \Omega_1 < R_2^2 \Omega_2$$

- Centrifugal force supported by wall pressure or magnetic pressure
- Use liquid metal or plasma for MRI, with appropriate external  $B_z$
- Use water or gas for nonlinear hydro instabilities



# Three Types of Laboratory Experiments

- **Hydrodynamic experiments using water**
- **MHD experiments using liquid metals**
- **Gas and plasma experiments**

# Hydrodynamic Experiments:

Do nonlinear hydro instabilities exist in Keplerian flows, and if so, how efficiently does it transport angular momentum?

## Full of Controversies

1. Richard & Zahn (2001): Yes
2. Beckley & Colgate (2002): Maybe no
3. Kageyama et al. (2004): Maybe no
4. Ji et al. (2006); Schartman et al. (2012): No
5. Paoletti & Lathrop (2011): Yes
6. Edlund & Ji (2014): No
7. Nordsiek et al. (2014): Maybe no



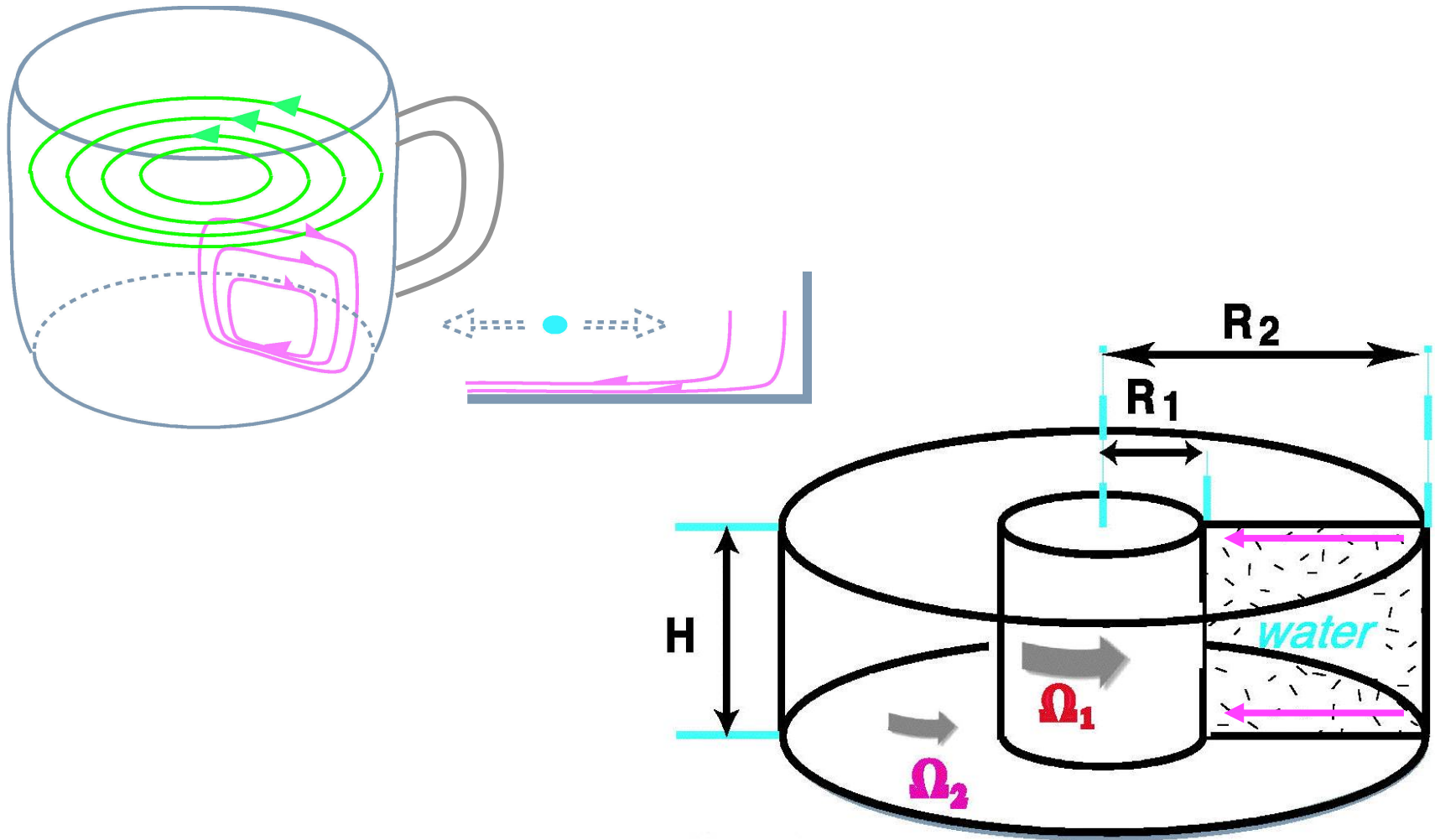
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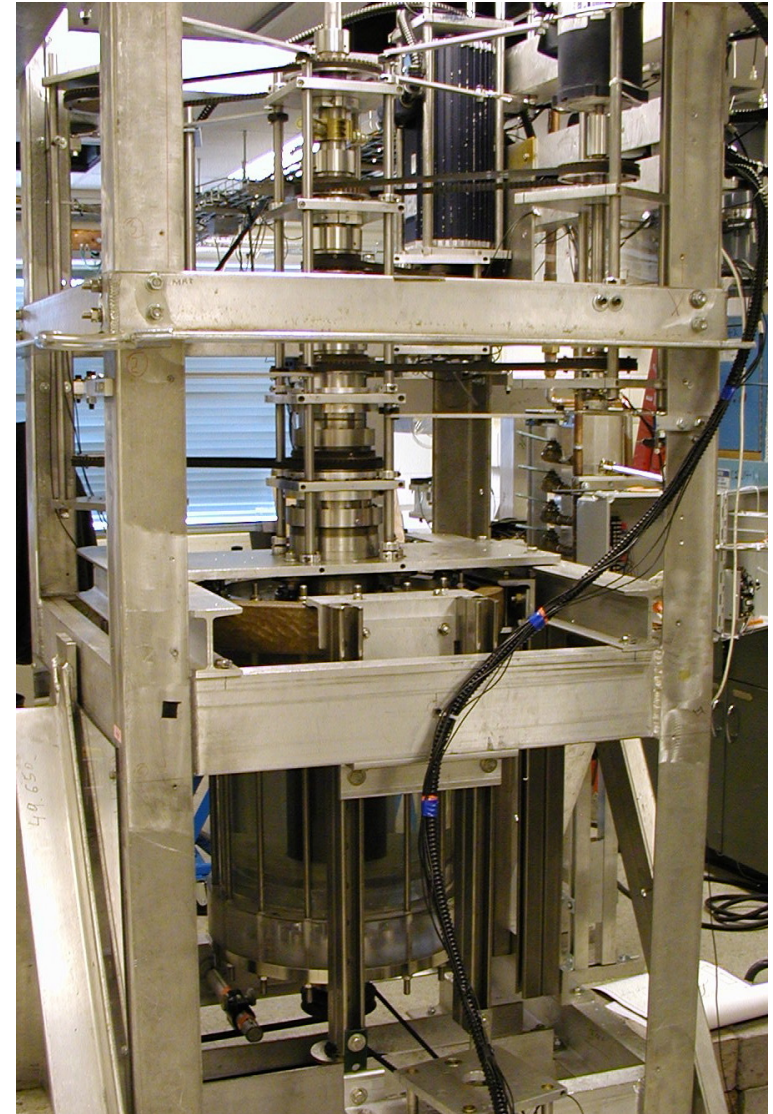
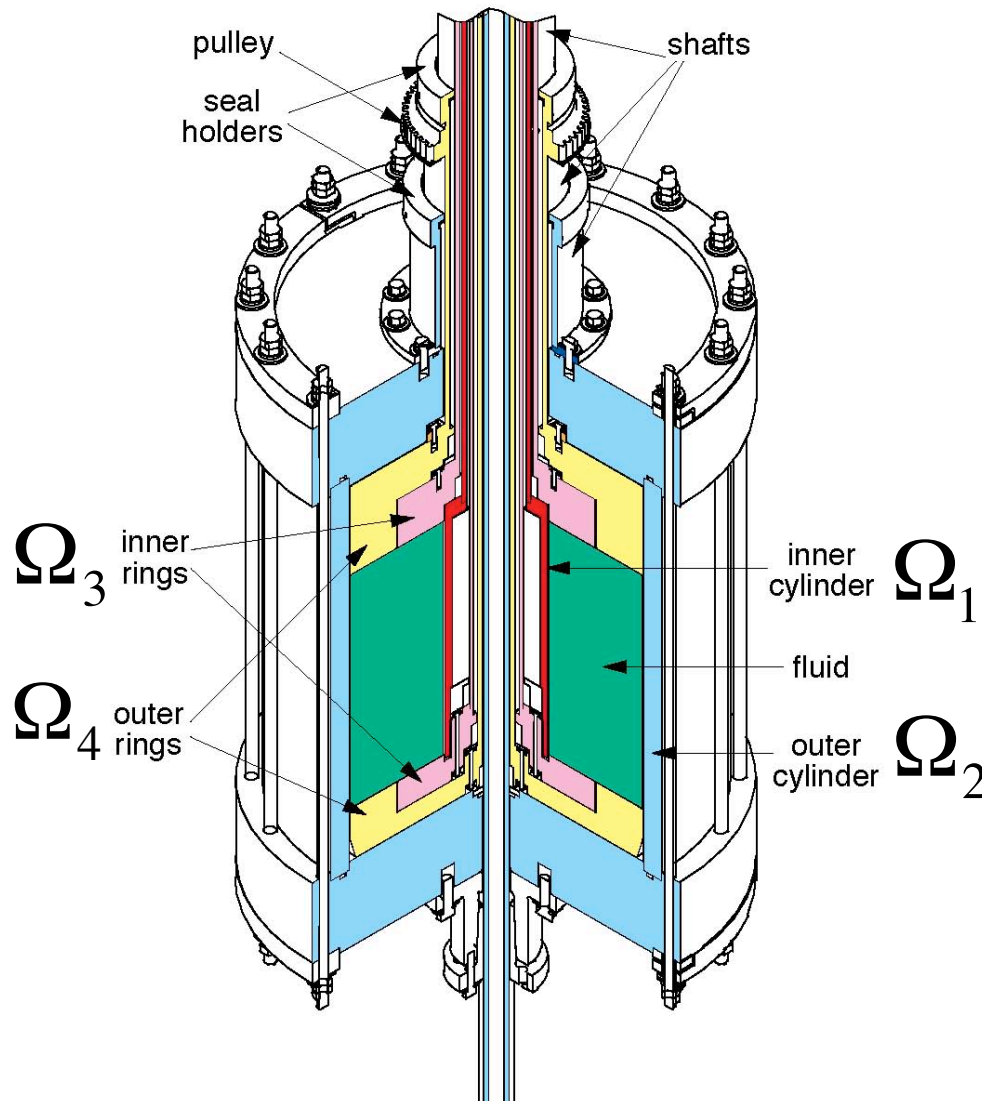
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# Imperfect Axial Boundaries Can Cause Significant *Ekman Effects*

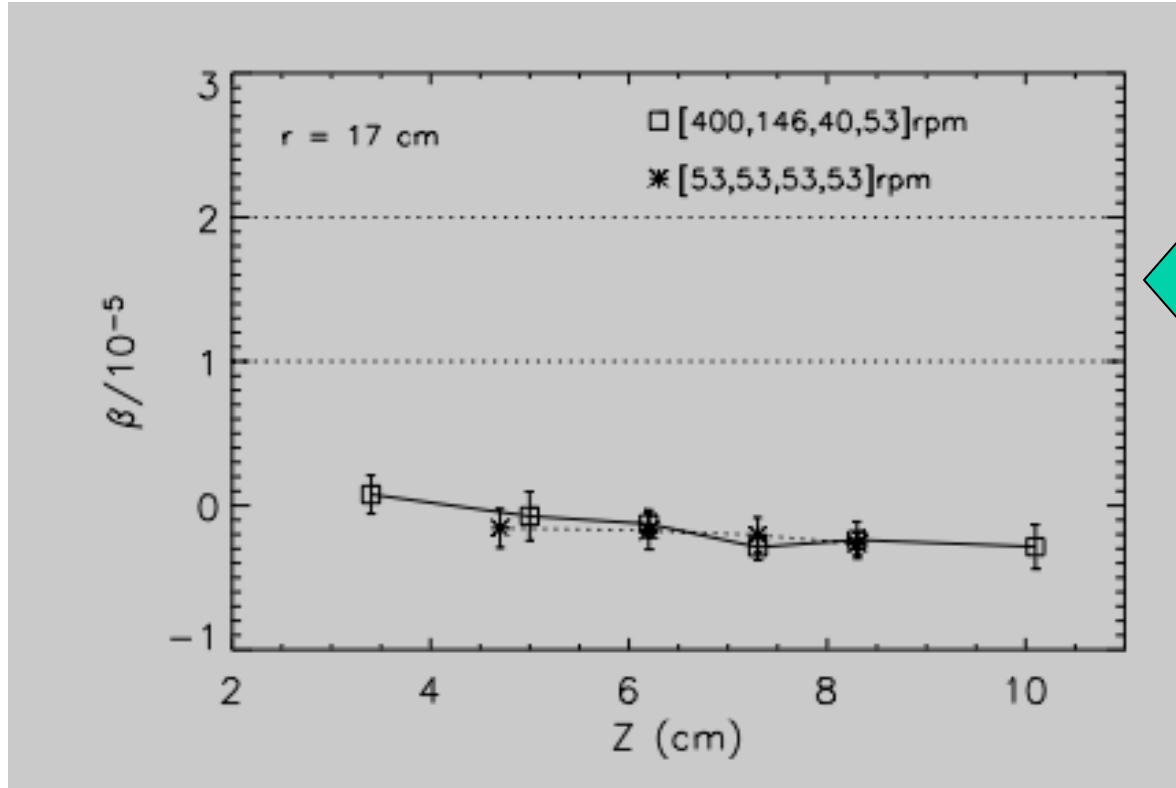


# Ji, Burin, Schartman, Goodman (2006)

Endcaps divided into two separate rings to control end effects or Ekman circulations,  $Re < 2 \times 10^6$



# Remarkably Quiescent in Quasi-Keplerian Flows at $\text{Re}=2 \times 10^6$ with Optimal Boundary Conditions



indistinguishable AMT from solid body flows

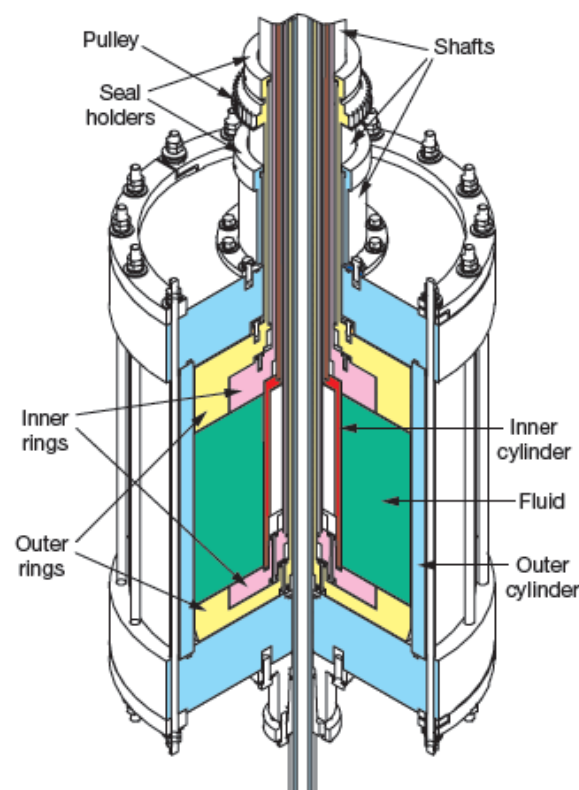
## LETTERS

# Hydrodynamic turbulence cannot transport angular momentum effectively in astrophysical disks

Hantao Ji<sup>1</sup>, Michael Burin<sup>1</sup>†, Ethan Schartman<sup>1</sup> & Jeremy Goodman<sup>1</sup>

The most efficient energy sources known in the Universe are accretion disks. Those around black holes convert 5–40 per cent of rest-mass energy to radiation. Like water circling a drain, inflowing mass must lose angular momentum, presumably by vigorous turbulence in disks, which are essentially inviscid<sup>1</sup>. The origin of the turbulence is unclear. Hot disks of electrically conducting plasma can become turbulent by way of the linear magnetorotational instability<sup>2</sup>. Cool disks, such as the planet-forming disks of proto-stars, may be too poorly ionized for the magnetorotational instability to occur, and therefore essentially unmagnetized and linearly stable. Nonlinear hydrodynamic instability often occurs in linearly stable flows (for example, pipe flows) at sufficiently large Reynolds numbers. Although planet-forming disks have extreme Reynolds numbers, keplerian rotation enhances their linear hydrodynamic stability, so the question of whether they can be turbulent and thereby transport angular momentum effectively is controversial<sup>3–15</sup>. Here we report a laboratory experiment, demonstrating that non-magnetic quasi-keplerian flows at Reynolds numbers up to millions are essentially steady. Scaled to accretion disks, rates of angular momentum transport lie far below astrophysical requirements. By ruling out purely hydrodynamic turbulence, our results indirectly support the magnetorotational instability as the likely cause of turbulence, even in cool disks.

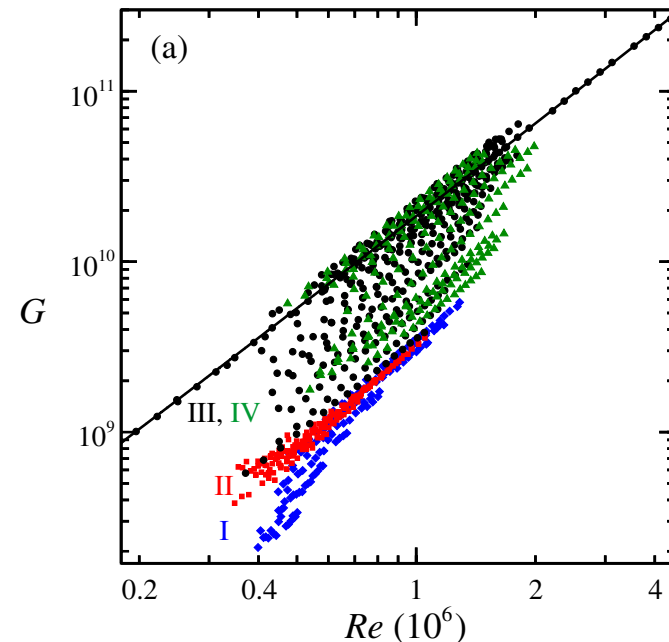
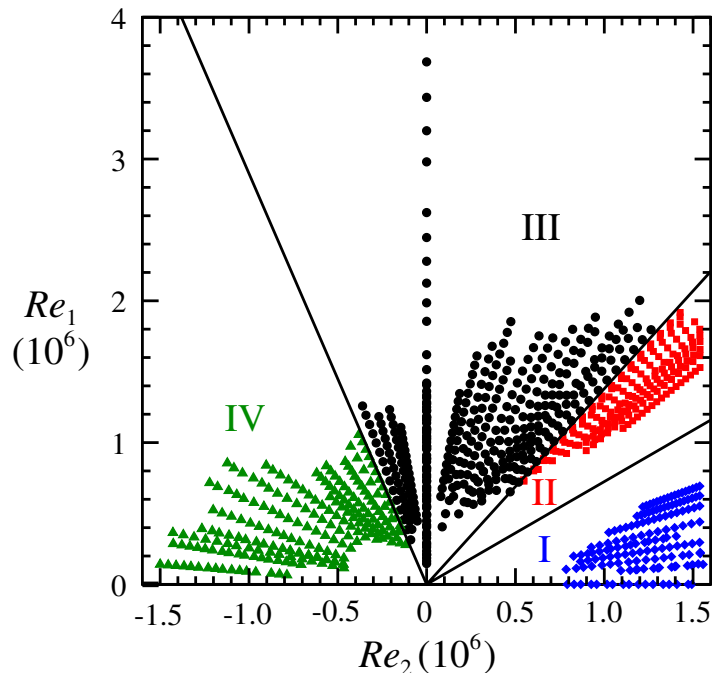
Our experiments involved a novel Taylor–Couette apparatus<sup>16</sup>. The rotating liquid (water or a water/glycerol mixture) is confined





# Paoletti & Lathrop (2011)

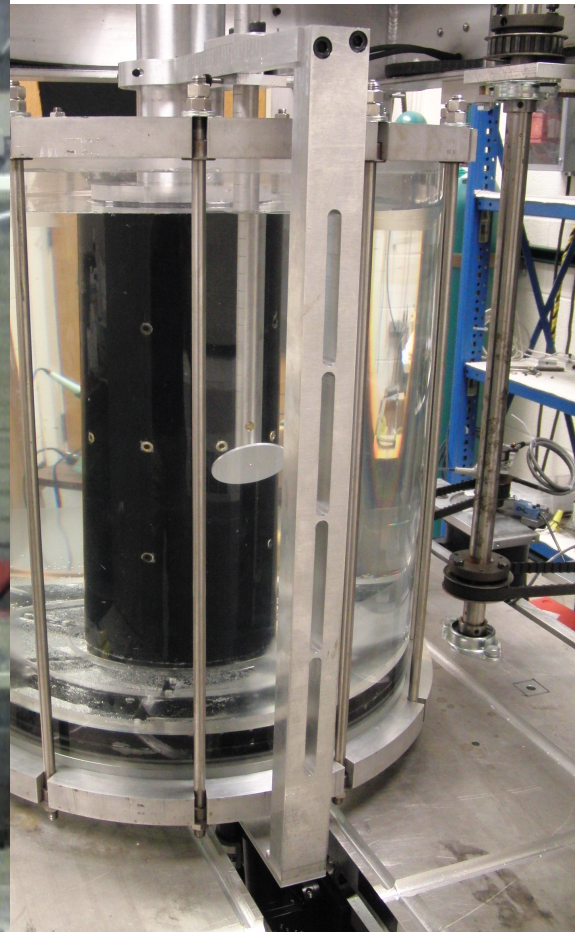
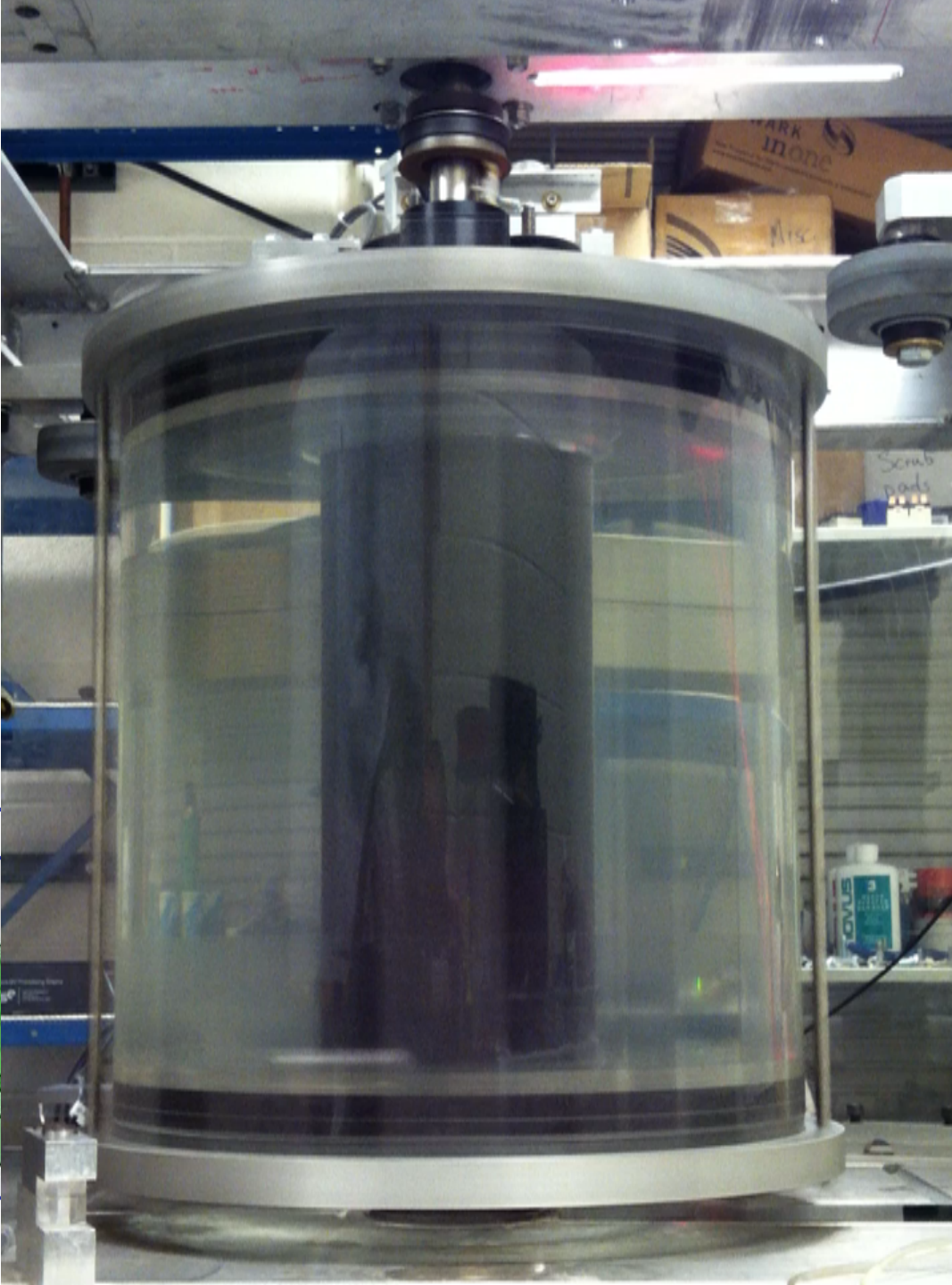
Endcaps attached to outer cylinder,  $Re < 2 \times 10^6$



Interpreted as turbulent from enhanced torque measured from a sleeve mounted on middle 1/3 of IC

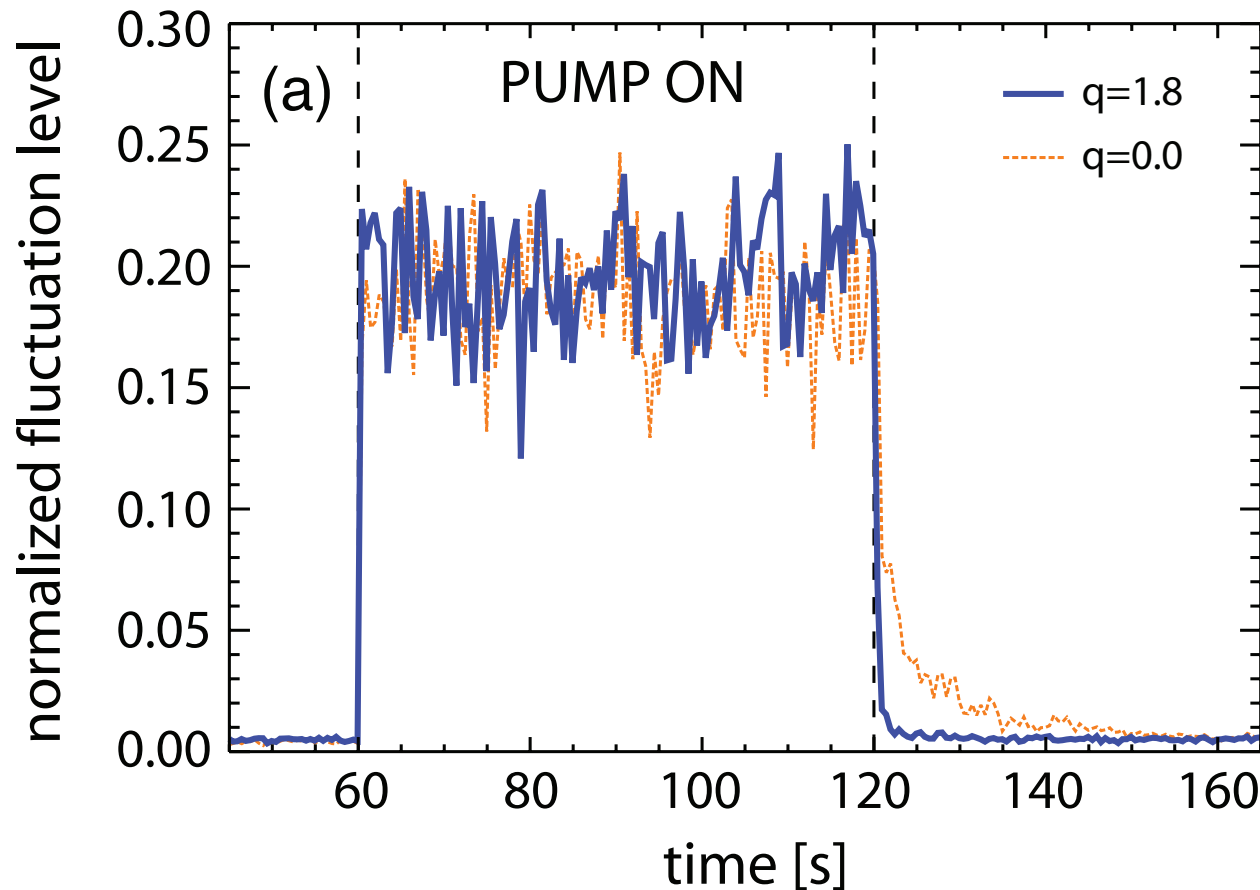
14)

rs,  $Re < 2 \times 10^6$



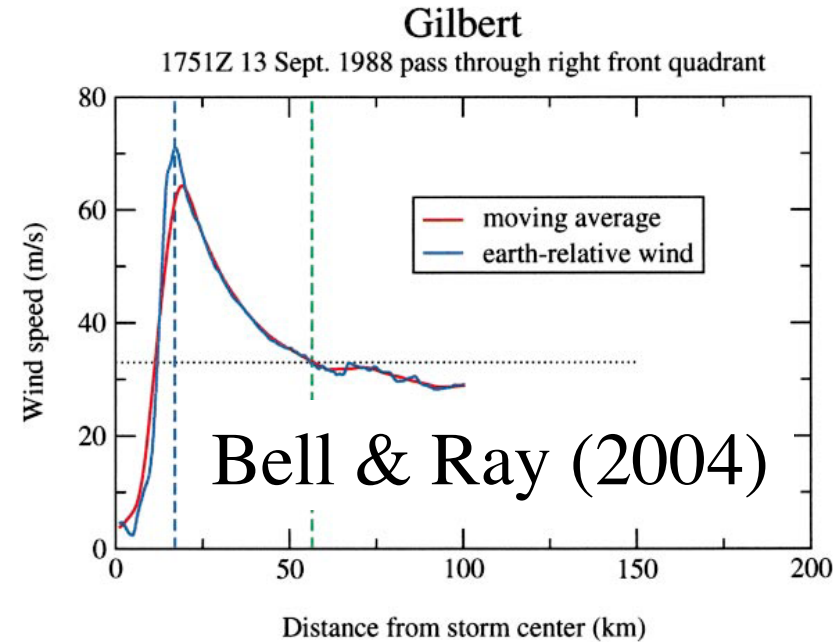


# All Attempts to Trigger Nonlinear Instabilities Have Failed



**q-K flows are robustly quiescent when and only when end effects are absent.**

# Ultimate Rotating Flows on Earth



- Flow outside the eye are quasi-Keplerian: that's why so robust?
- Can we disrupt it?



# Liquid Metal MHD Experiments:

Does MRI exist in quasi-Keplerian flows, and if so, how does it saturate to generate turbulence to transport angular momentum?

## Notoriously Difficult to Isolate the MRI:

1. Sisan et al. (2004): false alarm in a spherical geometry per Gissinger et al. (2011)
2. Stefani et al. (2006, 2009): found a helical version (HMRI) but unimportant for disks
3. Roach et al. (2012): Shercliff layer instability via boundary & magnetic field
4. Seilmayer et al. (2014): found an azimuthal version (AMRI) but astrophysical relevance unknown

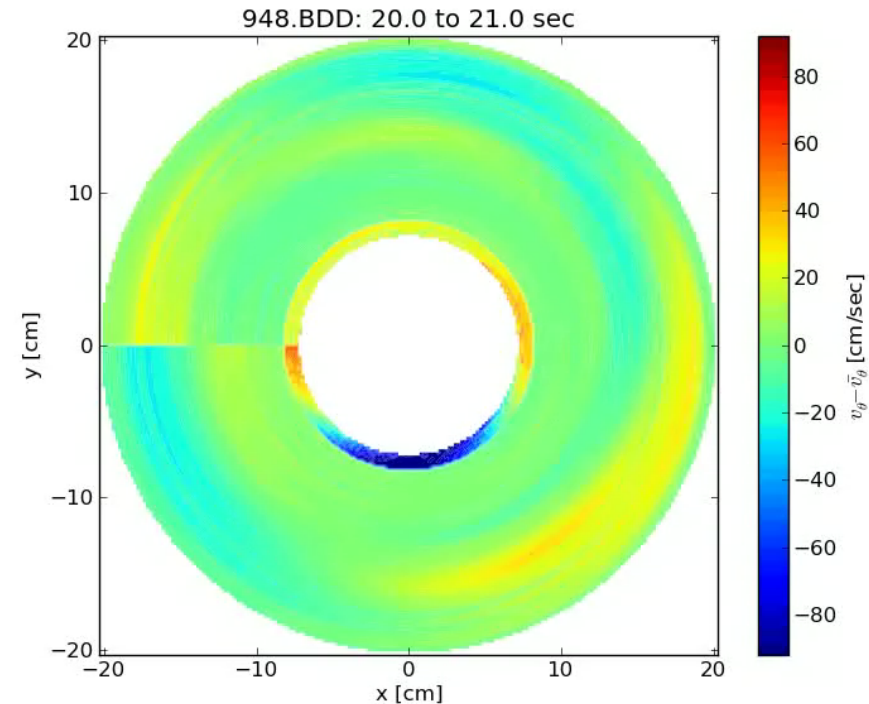
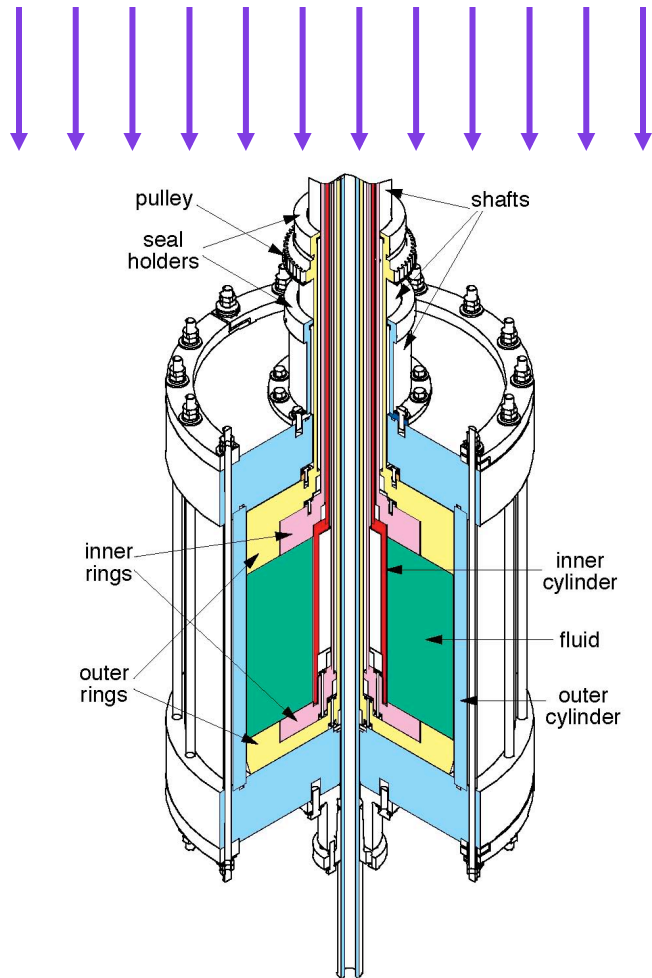
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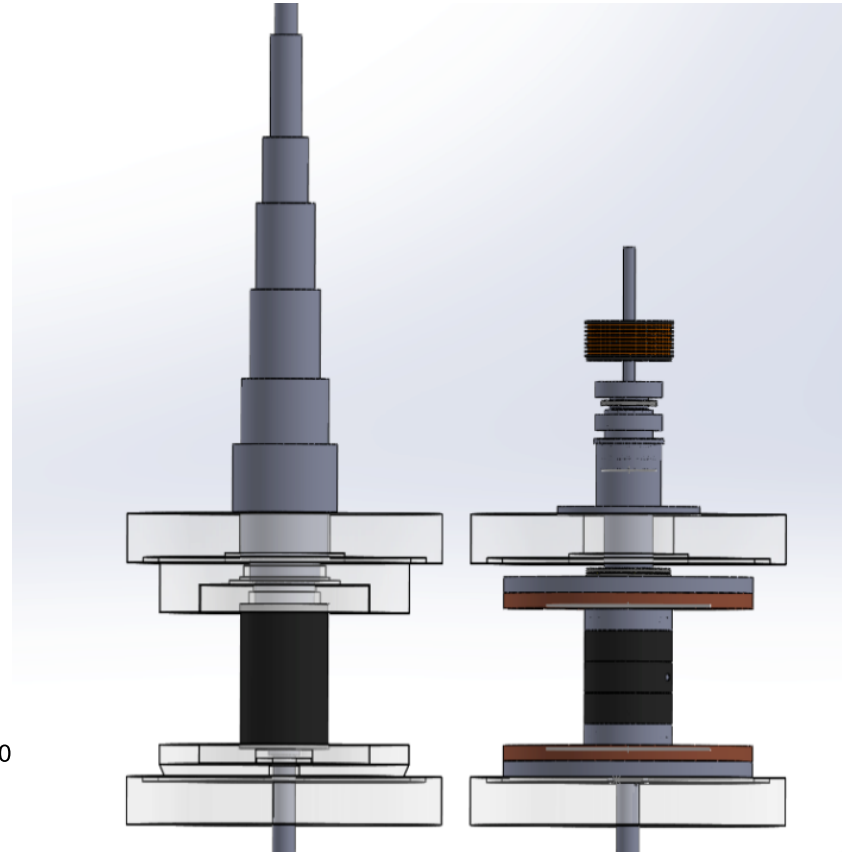
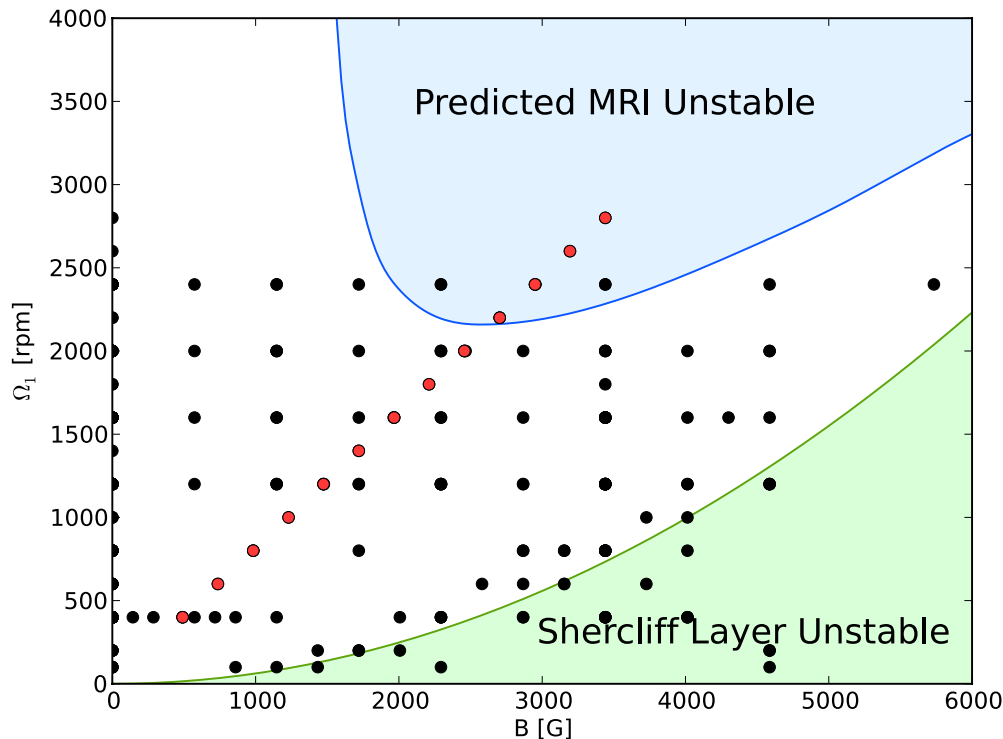
# Spiral Instability Detected When $B_z$ Is Imposed with Liquid Metal (GaInSn)



Flow measured by Ultrasonic Doppler Velocimetry

**Is this MRI?**

# No, It's a Boundary-Driven Instability! And MRI Conditions Are Achieved But Saturation Levels Are Too Small...



Upgrade underway with axial conducting boundaries  
for a **definite** detection of MRI

# Gas and Plasma Experiments:

Do nonlinear hydro instabilities, MRI exist, and what are effects due to compressibility, Hall effects, ambipolar diffusion, kinetic effects?

## Explorations Are Just Beginning:

1. Wang et al. (2008): unclear in a plasma gun geometry due to extensive fluctuations
2. Collins & Forest (2012): developed a new scheme to fast-spin an unmagnetized plasma
3. Ji et al. (2014): developing a new rotating gas scheme



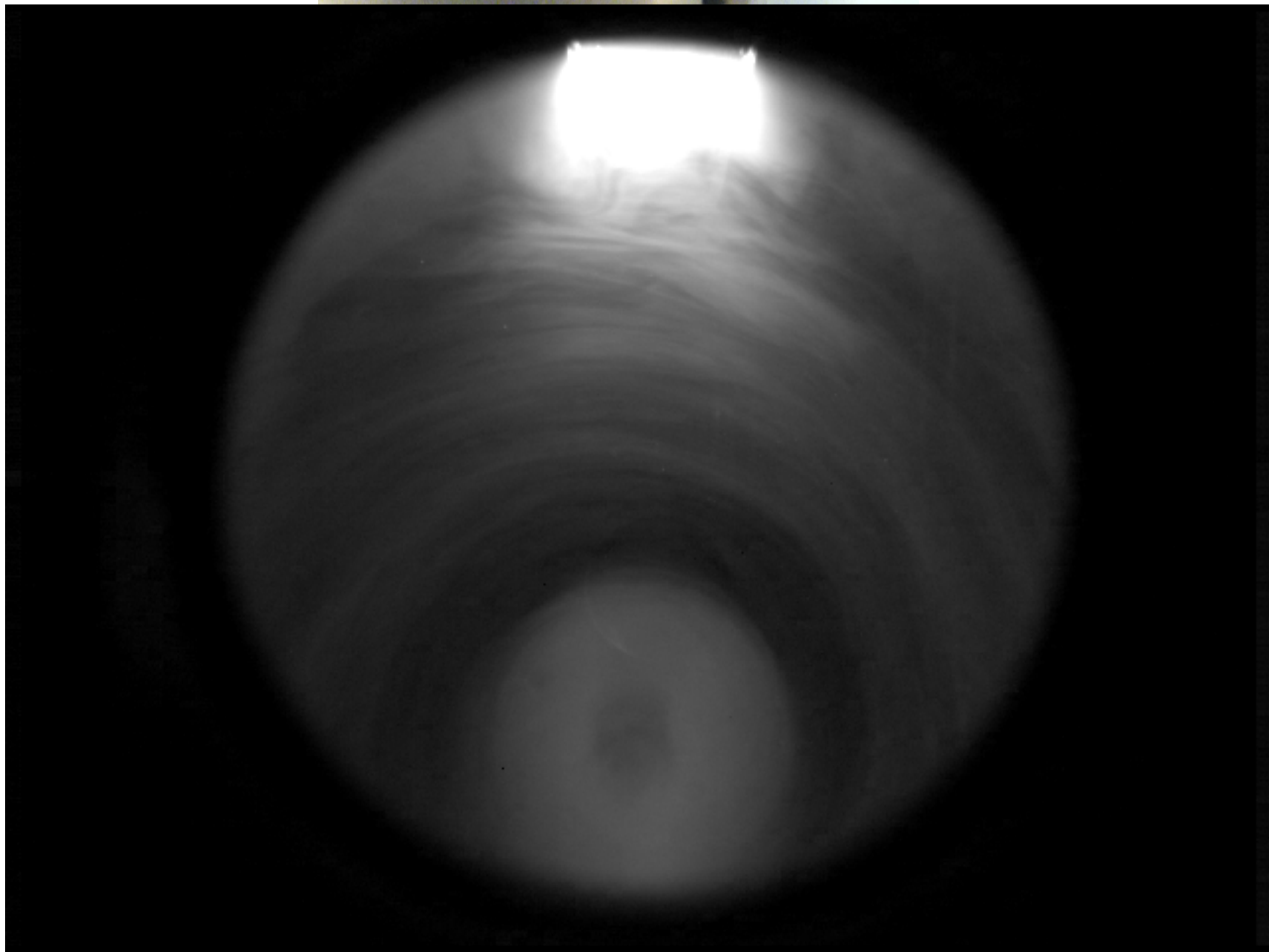
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# Summary

- Major scientific opportunities are growing in plasma astrophysics.
- Laboratory study of astrophysical processes and phenomena becomes increasingly possible and valuable, complementing numerical simulations.
- Angular momentum transport in accretion disks is a recent example:
  - ✓ Nonlinear hydro instabilities very unlikely – but why?
  - ✓ MRI detection may be near – either in liquid metal or plasma